

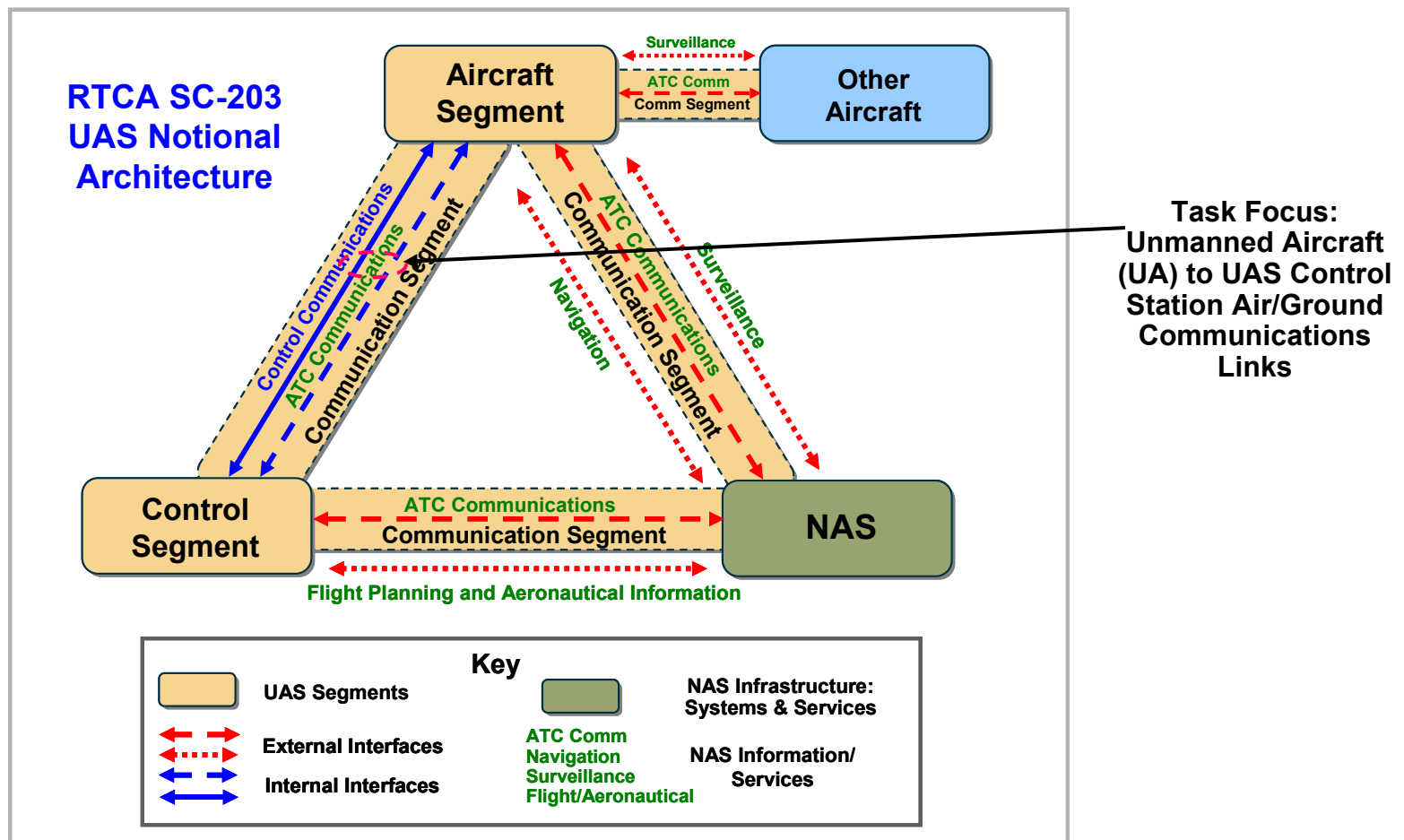
Unmanned Aircraft System Control and ATC Communications Bandwidth Requirements

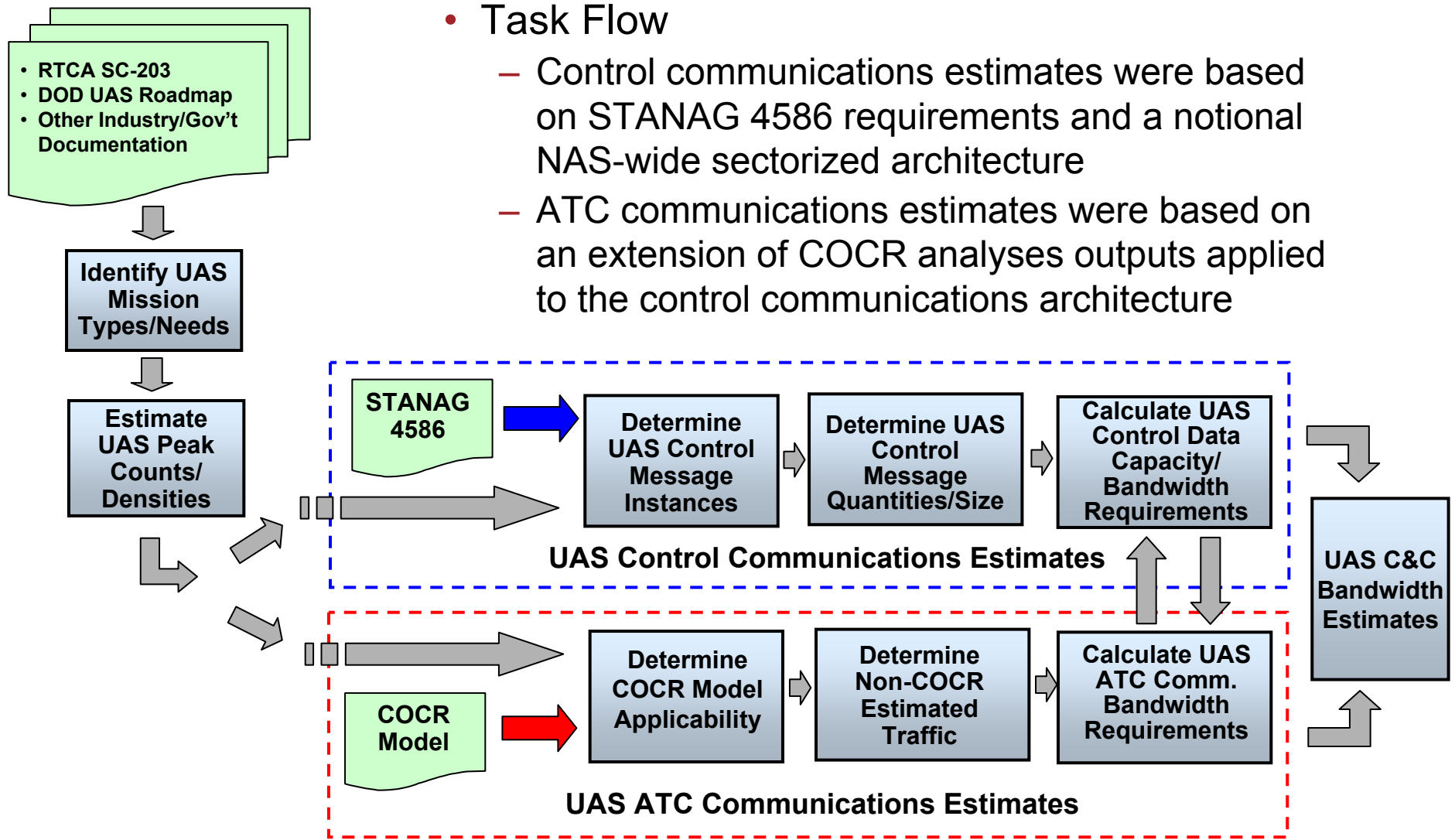
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May 3, 2007

- NASA GRC Access 5 Project team (2004-2006) defined functional communication requirements for unmanned aircraft systems (UAS)
- FAA/NASA/Eurocontrol Future Communications Study (FCS) (2004 – present) is identifying requirements and technologies for the future radio system
 - The Communications Operating Concept and Requirements (COCR) for the Future Radio System, which drives the technology evaluations, acknowledges the potential future impact of UAS, and implicitly includes UAS in its capacity analyses
- RTCA SC-203 (UAS) Control and Communications Working Group is addressing UAS communications spectrum requirements
- ITU World Radio Conference (WRC) planning activities include the U.S seeking an agenda item for WRC-11 addressing UAS communications spectrum requirements

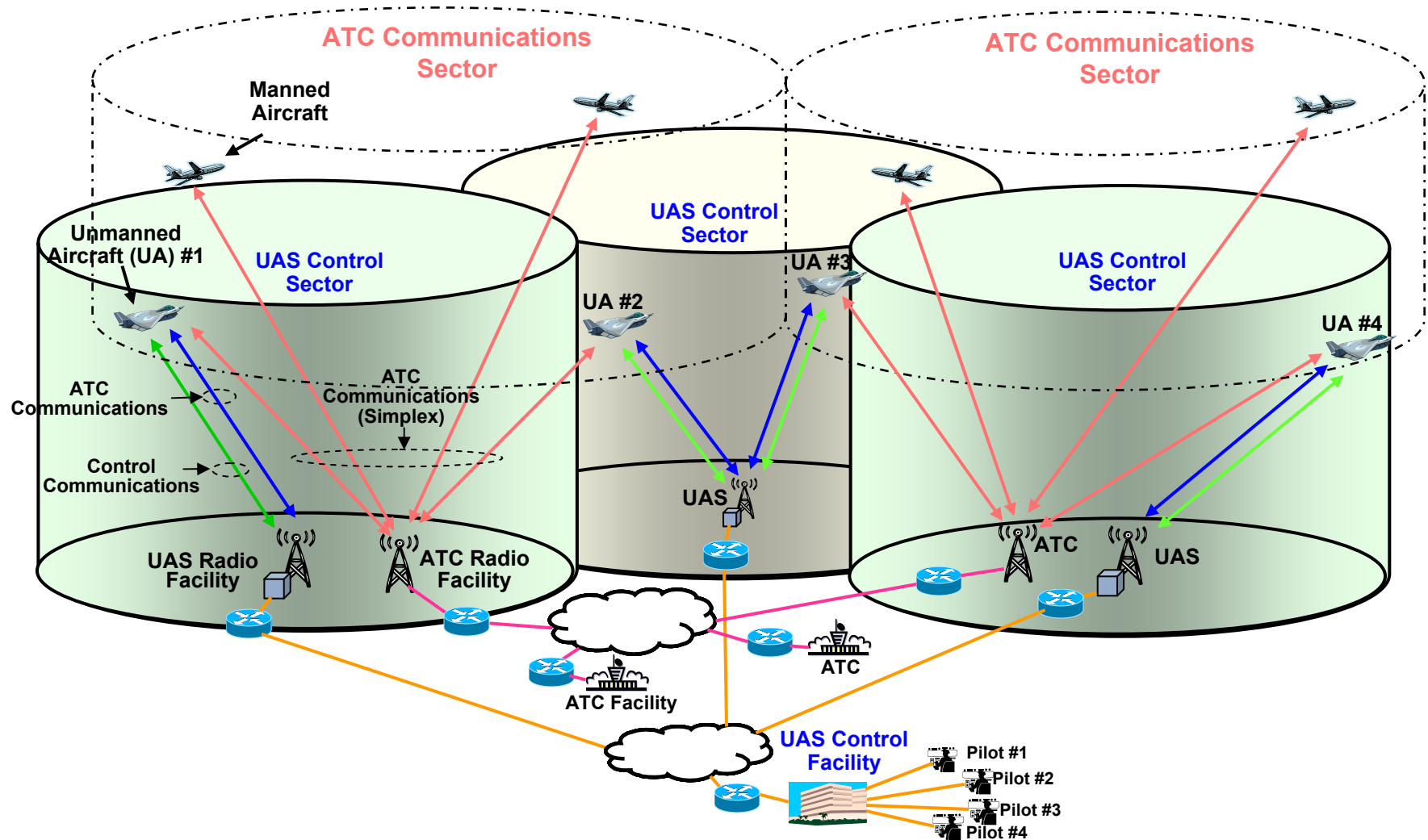
- Estimate future UAS Control and ATC Communications (C&C) bandwidth requirements for safe, reliable, and routine operation in the NAS, to support U.S. WRC preparation activities

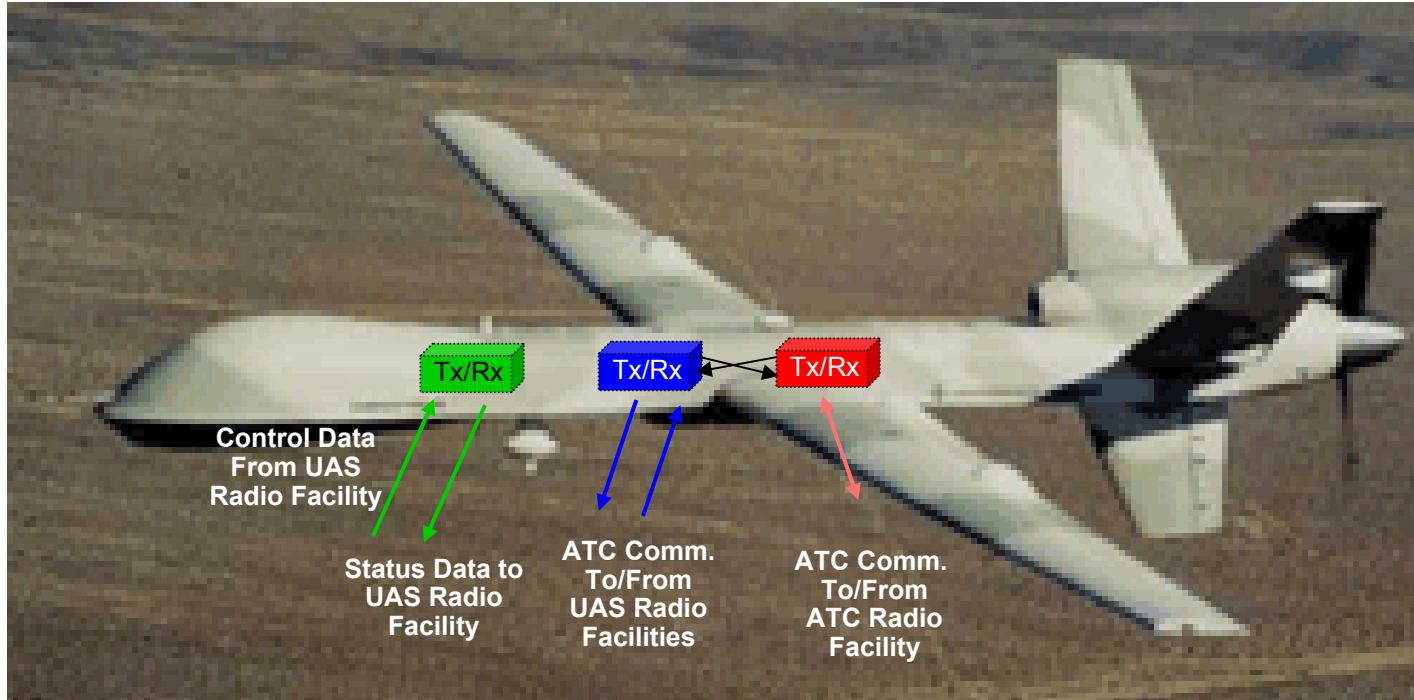




- UAS ATC communications services were assumed to be as defined in the COCR for air/ground services
 - Includes both data and voice services
- Study estimated C&C bandwidth requirements for new UAS radio facility to UA links only, assumed COCR ATC communications capacity requirements already accommodate ATC to UA links
- Study did not include UAS Sense and Avoid related communications links (e.g. radar, optical, video, etc.) or UAS payload related communications
- Study focused on long term bandwidth requirements for UAS approximately through 2030
- Potential aircraft or ground co-site interference issues were not considered

- This task was based on the concept that both ATC communications and UAS commands will be provided via a sectorized Air/Ground Line of Sight (LOS) communications architecture





- Up to seven links
 - Existing ATC Radio facility to UA Link: Channel for ATC communications shared with all aircraft in a sector (currently simplex VHF DSB-AM)
 - New UAS radio facility to UA Links:
 - Dedicated voice and data channels for ATC communications (uplink and downlink) – Up to four links
 - Dedicated channels for control communications (uplink and downlink) – Two links



UAS Specific Mission Types/Needs



- Evaluation of RTCA SC-203 UAS mission scenarios identified two main differences from traditional manned aircraft flight scenarios
 - Many proposed UAS missions include the need to “loiter” within particular airspace for periods from hours to months
 - Many UAS missions will not traverse airports or the TMA domains
- An assessment of the COCR traffic model led to the conclusion that this does not significantly impact the COCR ATS service capacity requirements, which implicitly include UAS traffic

- UAS bandwidth requirements are dependent on projected UAS traffic densities and hence Peak Instantaneous Aircraft Counts (PIACs)
- There are small number of projected estimates for civil UAS operation in the NAS
- Based on these studies, a UAS PIAC rough order of magnitude range of 5% – 10% of manned aircraft per service volume was assumed for this study
- COCR and Eurocontrol FCS test service volumes were used to determine the projected range of UA PIAC and UA densities

- UAS ATC communications service statistics and resulting capacity requirements were assumed to be identical to the manned aircraft ATS service statistics defined in the COCR

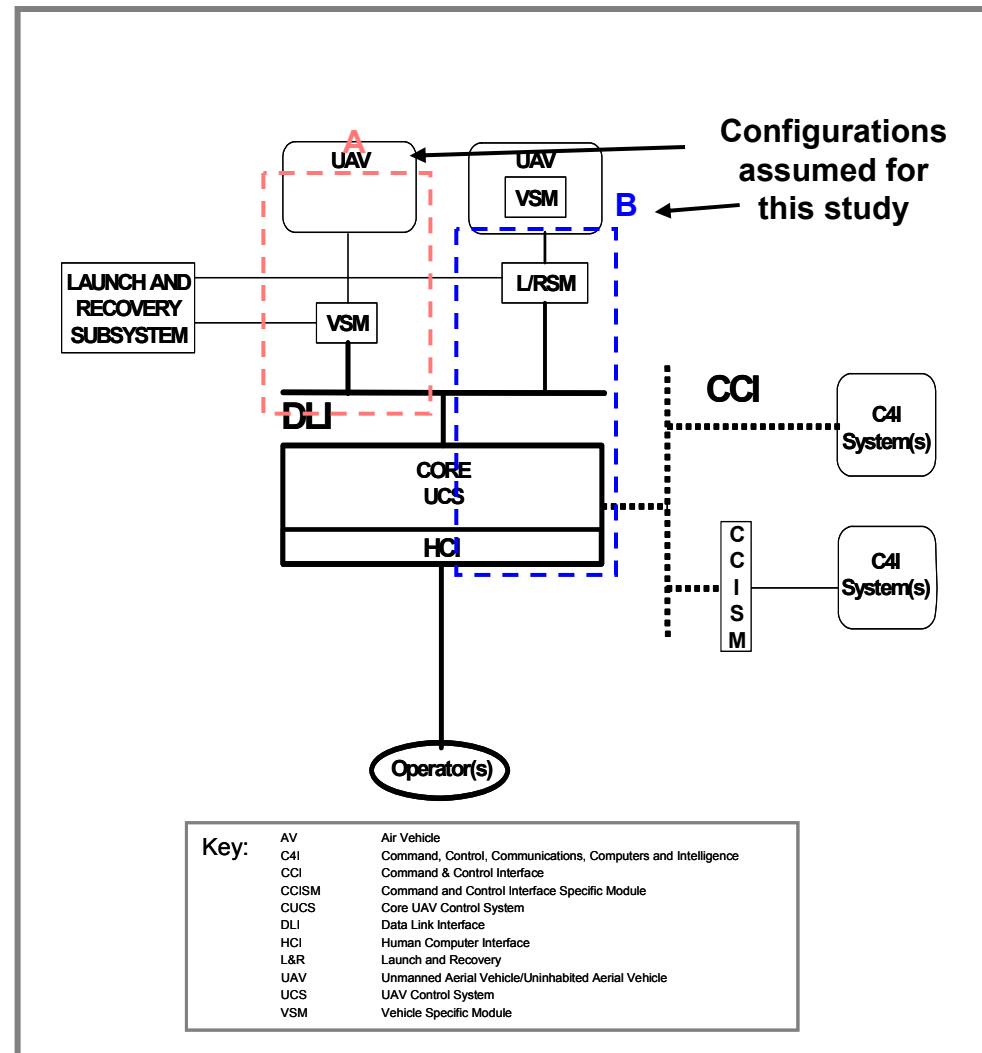
PHASE 2		APT SV Dep	APT SV Arr	TMA SV Dep	TMA SV Arr	ENR SV	ORP SV	AOA
Separate ATS	UL	6.9	1.8	5.6	3.8	5.7	5.7	6.7
	DL	6.2	1.9	6.8	1.6	6.7	8.5	12.5
	UL&DL	6.9	1.9	6.9	3.8	6.7	8.5	12.5

COCR V1.0 Air/Ground Data Capacity Requirements (kbps) for Each Aircraft using a Separate 'Channel' excluding the A-EXEC service – Phase 2 (Note: Includes “overheads associated with the network, integrity and security”).)

- UAS message instances for Control communications messages were based on implementation of STANAG 4586* compliant Data Link Interface (DLI) messages
 - STANAG 4586 is accepted as a generic standard for UAS message types and formats

* STANAG 4586, *Standard Interfaces of UAV Control System (UCS) for NATO UAV Interoperability*, Edition 2, March 2005

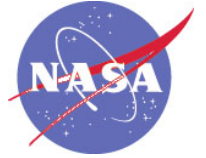
- DLI command/status messages flow between the VSM and the Core UCS (CUCS)
- STANAG 4586 accommodates the VSM residing either on the ground or within the aircraft (UAV)
- For this study, both configurations were considered
 - “A” assumes a non-networked, native or proprietary type RF link with some security overhead assumed
 - “B” implies an RF link that includes overhead for standards-based security and transport/network layer protocols





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UAS Control Message Quantities/Sizes

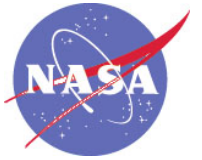


- Per STANAG 4586, unmanned aircraft control and status messages fall into three general categories
 - Initialization, configuration, and mission upload messages exchanged preflight
 - Configuration messages also can be exchanged infrequently during flight as necessary if the operating mode or configuration of the aircraft is changed
 - Control messages sent to control the aircraft and its engines
 - The frequency of these messages is highly related to the level of autonomy characterizing the aircraft
 - Status messages sent (pushed) by the aircraft
 - These report dynamic changes in aircraft movements, direction, orientation, engine operation, etc.
 - These messages can be sent very frequently
 - Typical update rates are 1 to 10 times per second for critical parameters according to UAS manufacturers
 - **These updates rates are the major drivers in determination of aggregate aircraft to ground data rate, and hence bandwidth**



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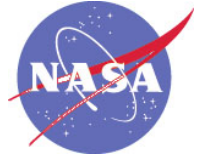
UAS Control Message Quantities/Sizes (2)



- As recommended by STANAG 4586, messages for Configuration B included the following overhead
 - STANAG 4586 wrapper overhead: 34 bytes
 - Network/Transport layer overhead
 - Space Communications Protocol Specification (SCPS) Transport Protocol (SCPS-TP) with UDP messages: 8 byte header
 - IPv6: 40 byte header
 - Security overhead
 - SCPS Security Protocol (SCPS-SP) with 14 byte overhead
 - 2 byte header
 - 12 byte (96 bit) length Integrity Check Value (ICV)
 - Key management overhead was not included
 - Messages for Configuration A were assumed to include 10% security overhead, and not include DLI wrapper, or transport/network layer overhead



- Characterized by a two way message exchange as the aircraft's operating parameters are initially configured
- Total amount of data exchanged is modest
 - Less than 15K bytes sent to the UA
 - Less than 25K bytes sent to the control station
- Several hundred bytes are also exchanged during each handoff from one UAS radio control station to another (not shown in table)

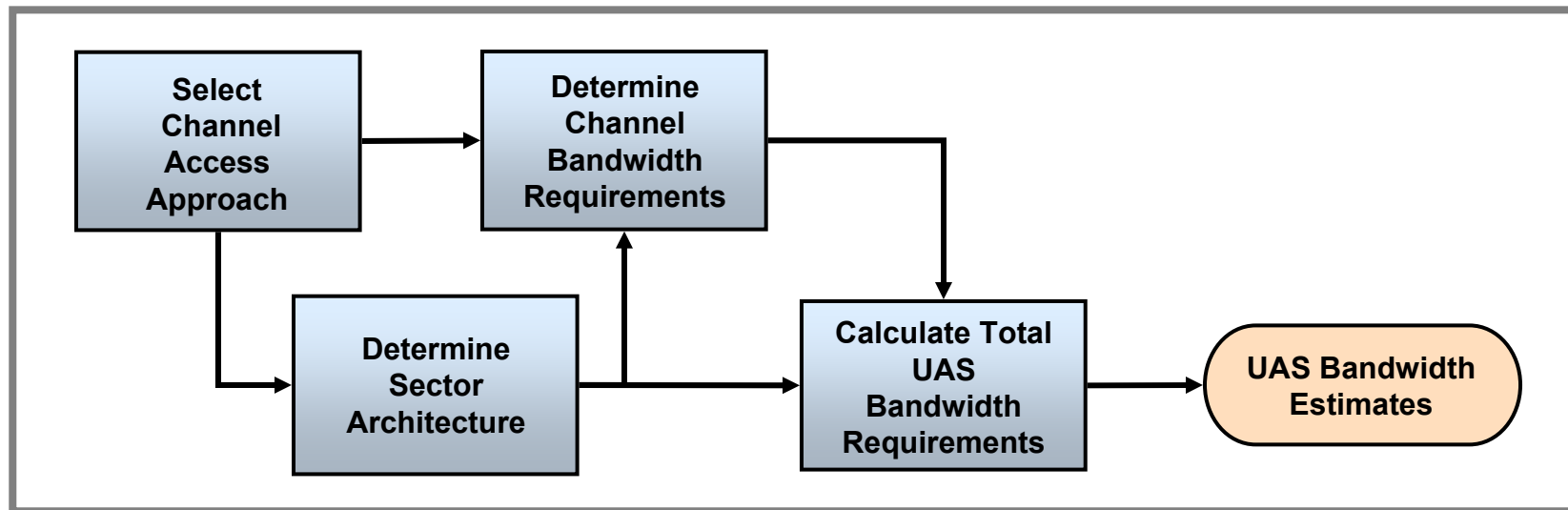


- This also requires relatively few bytes exchanged
- Above example is for a loitering type mission

CUCS (Ground) Originated										VSM (Aircraft) Originated									
STANAG	Aperiodic: # of msg sent per Phase of Flight	Periodic: Message Rate #/sec	Msg length w/Transport Layer Overhead (bytes)	Msg length w/Security Overhead (bytes) ¹	Msg length with Security Overhead (bytes) ²	Aperiodic: Total Bytes per Phase of Flight	Periodic: Bits/sec	Periodic Bit/Sec w/o Transport/ Network Overhead		STANAG	Aperiodic: # of msg sent per Phase of Flight	Periodic: Message Rate #/sec	Msg length w/Transport Layer Overhead (bytes)	Msg length w/Security Overhead (bytes) ¹	Msg length with Security Overhead (bytes) ²	Aperiodic: Total Bytes per Phase of Flight	Periodic: Bits/sec	Periodic Bit/Sec w/o transport/n etwork overhead	
4586										4586									
Msg #	Flight	Rate #/sec	(bytes)	(bytes)	(bytes) ¹	(bytes) ²	per Phase of Flight	Bits/sec	Network Overhead	Msg #	Flight	Rate #/sec	(bytes)	(bytes)	(bytes) ¹	(bytes) ²	per Phase of Flight	Bits/sec	
Vehicle Steering																			
Command	43		0.2	66	100	148	162	0	259.2	116.2									
Engine Command	45		0.1	21	55	103	117	0	93.6	18.5									
Subsystem Status																			
Request	1000		5	20	54	102	116	0	4640	880.0									
Subsystem Status																			
Detail Request	1001	1		20	54	102	116	116	0	0.0									
Inertial States																			
Air and Ground	101										2	84	118	166	180	0	2880	1478.4	
Relative States	102										2	64	98	146	160	0	2560	1126.4	
Body-Relative																			
Sensed States	103										10	40	74	122	136	0	10880	3520.0	
Vehicle Operating																			
States	104										2	145	179	227	241	0	3856	2552.0	
Engine Operating																			
States	105										5	36	70	118	132	0	5280	1584.0	
Vehicle Light States																			
Data Link Status	107										1	36	70	118	132	0	1056	316.8	
Report																			
Pedestal Status	501										1	38	72	120	134	0	1072	334.4	
Report																			
Subsystem Status	503										0.2	58	92	140	154	0	246.4	102.1	
Report																			
Subsystem Status	1101										1	22	56	104	118	0	944	193.6	
Alert Message	1100																		
116																			
Aggregate Data Rate From Control Station (bps)																			
B 4,993 1,015 A Networked Non-Networked																			
Aggregate Data Rate From Aircraft (bps)																			
B 28,774 11,208 A Networked Non-Networked																			

- These include the major driver of UAS link capacities: aircraft status and telemetry messages
 - Aggregated status/telemetry message data rate is tens of thousand of bits per second – almost 29 kbps is estimated above (Configuration B)
 - Control message traffic is aperiodic and varies according to aircraft autonomy
 - A average aggregate data rate was estimated to be around 5 kbps (Config. B)

- A parallel process was used to estimate Control and ATC Communications bandwidth requirements for the links of interest



- UAS Control Communications
 - Dedicated full duplex channels are needed because contention based protocols could not efficiently provide sufficient Quality of Service in terms of latency and availability
 - An FDMA system consisting of one set of asymmetrical dedicated full duplex channels per Ground Station to UA link was assumed for bandwidth estimation purposes
- ATC Communications
 - The UA to UAS Control Facility link is analogous to the hard wired circuit that connects a manned aircraft pilot with his aircraft radio
 - On a manned aircraft this is a dedicated high availability, low latency “link”
 - An FDMA system consisting of two dedicated duplex channel pairs per Ground Station to UA link (voice and data) was assumed for bandwidth estimation purposes
 - For implementation, voice and data traffic could be multiplexed, resulting in one duplex ATC Communications uplink and downlink channel pair

Access	Advantages	Disadvantages
Dedicated	<ul style="list-style-type: none"> • Minimum latency • Predictable availability • Simpler • Possible to use non-aviation standard technologies (e.g. P25) 	<ul style="list-style-type: none"> • Bandwidth intensive • No current ICAO standard
Shared	<ul style="list-style-type: none"> • Minimum potential bandwidth impact • Possible use of existing ICAO standard (e.g. VDL M3) 	<ul style="list-style-type: none"> • More complex • Availability issue - channel contention for two links rather than for one link • Existing standards like VDL-M3 might not work without modifications, which would have to be standardized

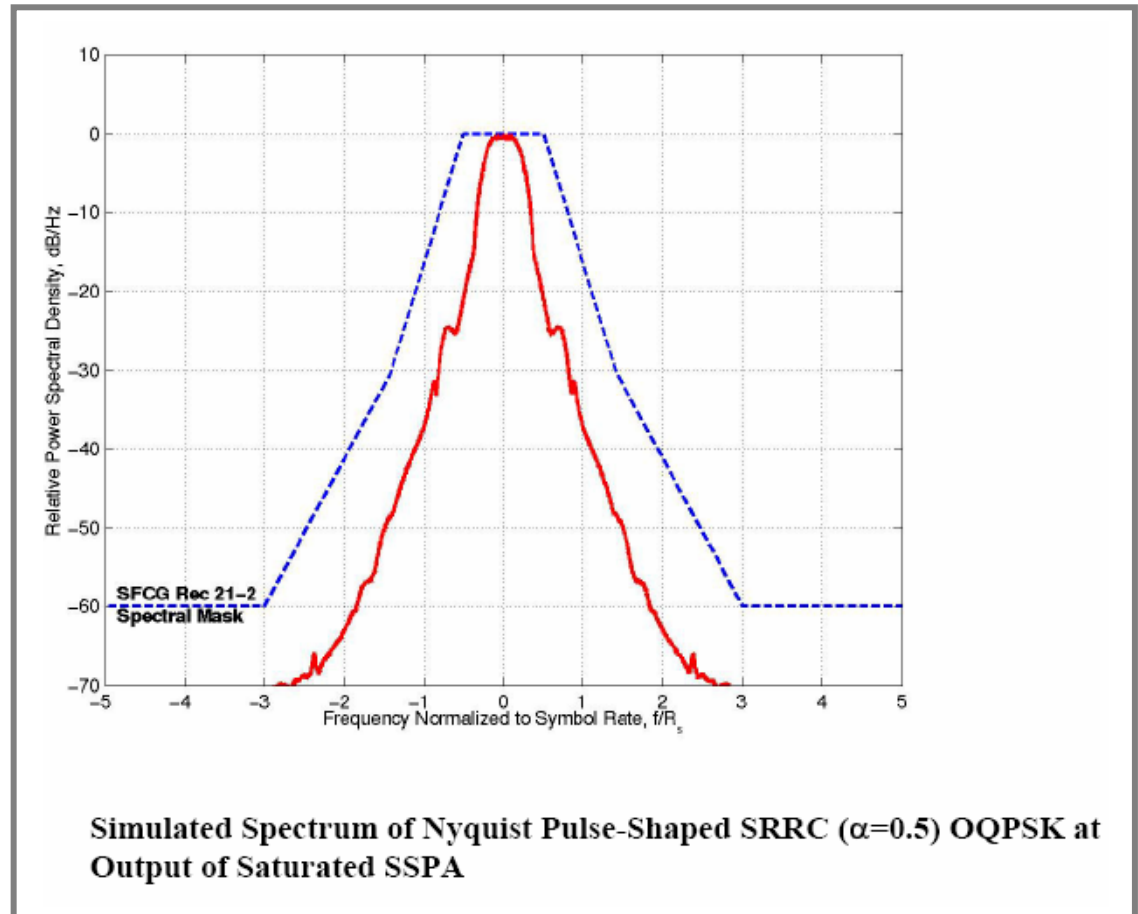
- UAS Control Communications Modulation type

- SRRC ($\alpha = 0.5$) OQPSK was selected as the modulation used in the link budgets, as it combines good E_b/N_0 performance with good interference susceptibility performance

- Link budget parameters

- Spectral efficiency at 99% bandwidth (Occupied Bandwidth) = $0.88R_s$
- Required BER = 10^{-6}

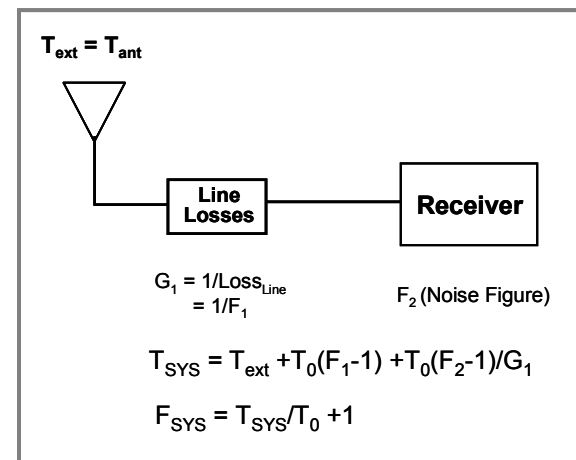
Link FEC Coding	Theoretical E_b/N_0 (dB)
Uncoded	11.5
3/4 Conv. FEC Only	6.5
CC RS+3/4 Conv. FEC	4.5
1/2 Conv. FEC Only	5.0
CC RS+1/2 Conv. FEC	3.0



Note: R_s is the coded symbol rate, i.e. after the FEC encoder, not the channel symbol rate after the modulator.

- Selected UAS Control Communications Link Parameters
 - Frequency Band
 - UAS control communications link budgets were based on an implementation in the aeronautical “L-Band,” that is 960 – 1215 MHz
 - This yields a 2 dB range in free space path loss across this band
 - 1088 MHz (center of band) was used in the link budgets for path loss
 - System Noise Temperature
 - Used line loss values consistent with typical aeronautical application link budgets
 - System noise temperature was dependent on 100K external noise, line losses, and receiver noise figure

Calculating System Noise Temperature and Noise Figure



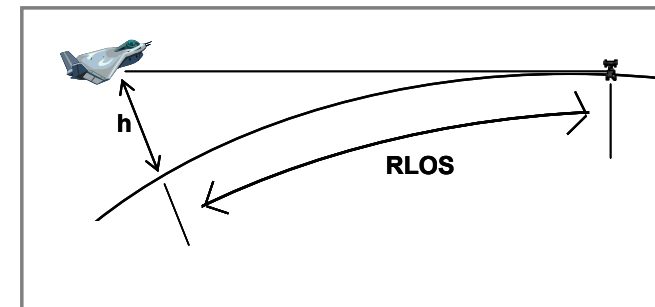
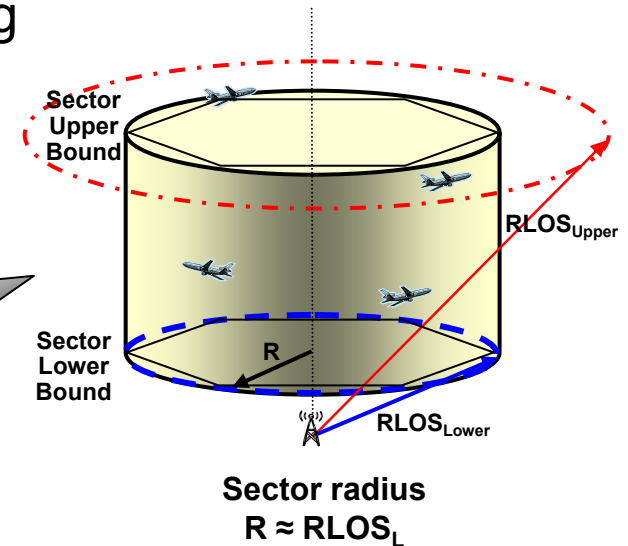
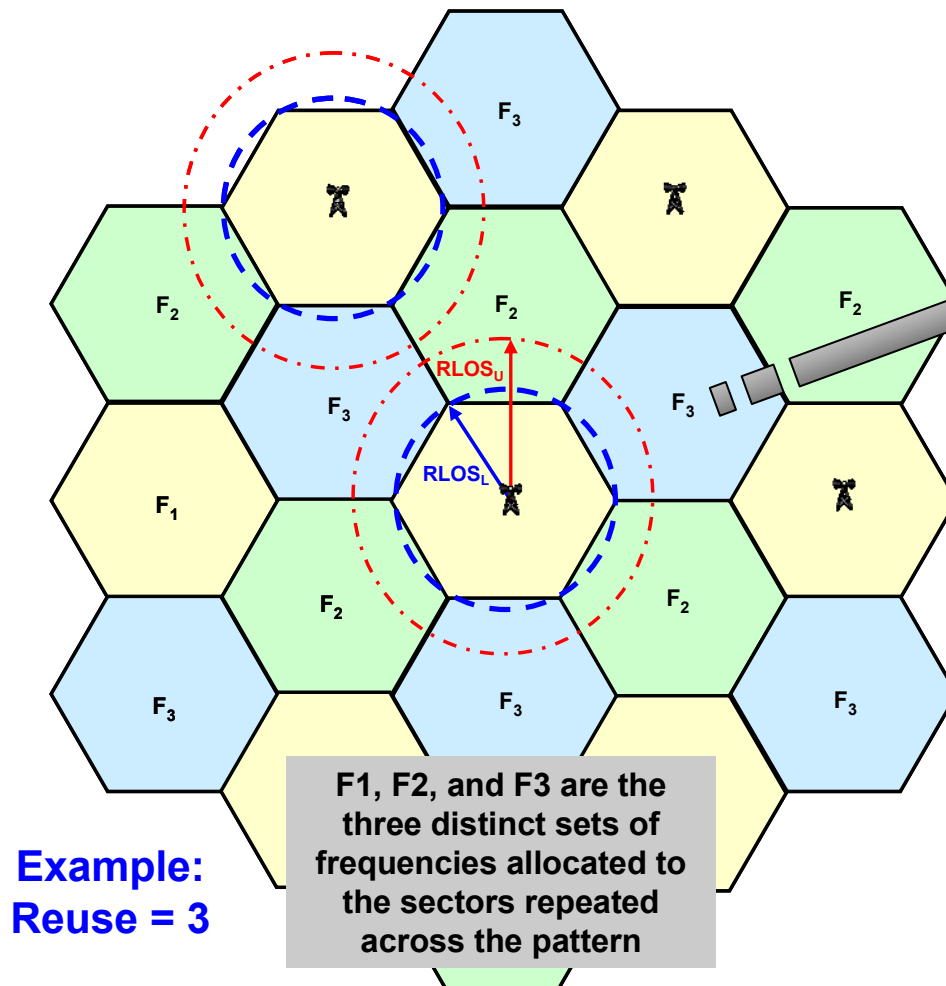
- Antenna Gains
 - Assumed 6 dBi gain for the ground system antenna consistent with typical aeronautical application link budgets
 - Assumed 0 dBi gain for the UA antenna consistent with UAT MOPS values

- UAS ATC Communications Link Parameters
 - ATC voice was assumed to be 4800 bps vocoded data, and the same modulation and FEC coding parameters used for the Control communications links were applied
 - Duplex (separate uplink and downlink) channels were assumed
 - This may be necessitated by the end-to-end latency issues with vocoded speech and the burden of two “hops”
 - COCR data capacity values were used for ATC data communications
 - Duplex (separate uplink and downlink) channels were assumed
 - Autonomous Operations Area (AOA) provided a conservative upper bound for the larger, higher altitude service volumes

PHASE 2		APT SV Dep	APT SV Arr	TMA SV Dep	TMA SV Arr	ENR SV	ORP SV	AOA
Separate ATS	UL	6.9	1.8	5.6	3.8	5.7	5.7	6.7
	DL	6.2	1.9	6.8	1.6	6.7	8.5	12.5
	UL&DL	6.9	1.9	6.9	3.8	6.7	8.5	12.5

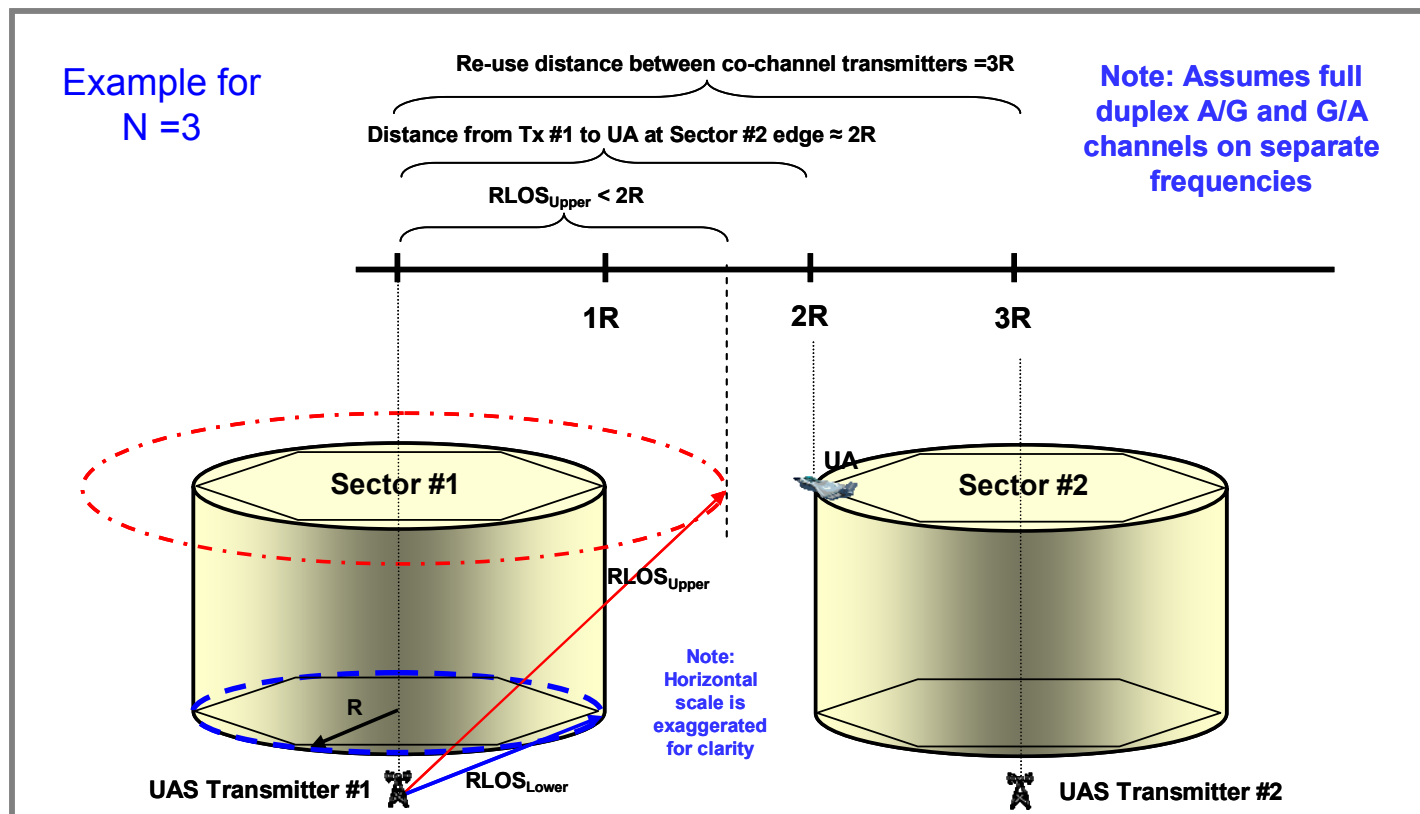
COCR V1.0 Air/Ground Data Capacity Requirements (kbps) for Each Aircraft using a Separate ‘Channel’

- Consistent with standard telecommunications practice, the sector architecture was defined using hexagonal tiling

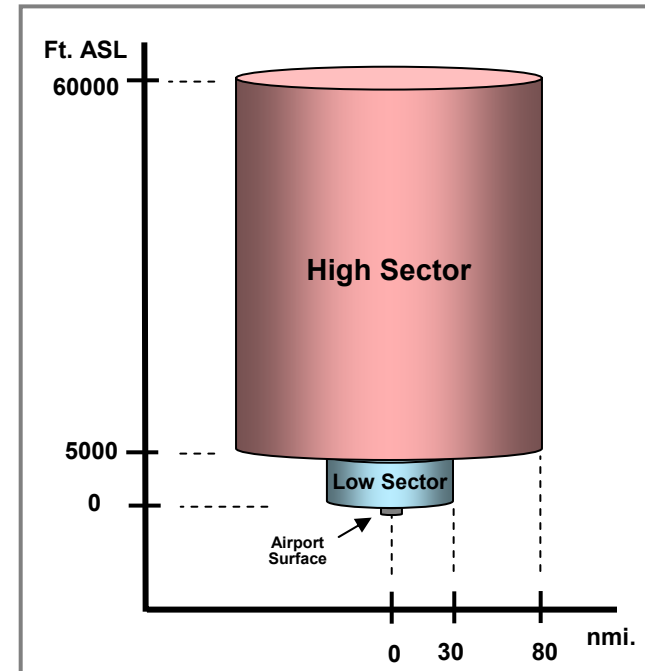


Radio line of sight = $RLOS \text{ (nmi)} = 1.23\sqrt{h}$, where h is in feet (4/3 earth effective radius assumption); for $h = 60000$ feet, RLOS is 301 nmi.

- To assure coverage $R < RLOS_{Lower}$, where
 - R is the sector radius
 - $RLOS_{Lower}$ is the radio line of sight (RLOS) of the lower boundary of the sector
 - For sectors with lower boundary of ground level, this condition is satisfied through typical ground station antenna heights and take-off/landing aircraft altitudes; at 1000 ft, $R_{LOS} = 39$ miles
- To avoid co-channel interference (for duplex channels) $RLOS_{Upper}/R < (Q - 1)$, where
 - $RLOS_{Upper}$ is the radio line of sight of the upper boundary of the sector
 - Q is the co-channel re-use distance = $SQRT(3N)$, where N is the cluster size (re-use factor)



- A sector architecture was defined to avoid multiple layers and the need for significant sub-banding
- It features $N = 9$ re-use for the High Sector level, and $N = 7$ for the Low Sector level
- Separate sub-bands for uplinks and downlinks would be desirable to provide co-channel interference protection



Cylindrical Sectors	High Sector	Low Sector
Sector radius (nmi)	80	30
Sector top (ft)	60000	5000
Sector bottom (ft)	5000	0
Sector height (nmi)	9.1	0.8
Circular Sector area (nmi ²)	20,106	2,827
Hexagonal Sector Area (nmi ²)	16,628	2,338
Hexagonal Sector volume (nmi ³)	150,511	1,924
Ratio: Circular/Hexagonal Area	1.21	
Radio line of sight at top (nmi)	301	87
Radio line of sight at bottom (nmi)	87	0
RLOS _{top} /RLOS _{bottom}	3.46	
RLOS _{top} /Sector radius	3.77	2.90
Cluster Size N	9	7
Reuse distance -1	4.20	3.58

- Link budgets were performed to derive acceptable bandwidth and power parameters

- All link budgets were based on the following assumptions:
 - Required BER = 10^{-6}
 - At least 10 dB required link margin

Link Budget Parameter	High Sector 5000 - 60000 ft	Low Sector 0 - 5000 ft	Airport Surface
Air-to-Ground Slant Range (nmi)	80	30	5
Transmit Power (dBm)	41.8	41.8	41.8
Transmit Line losses (dB)	-3	-3	-3
Transmit Antenna Gain (dBi)	0	0	0
Transmit EIRP (dBm)	38.8	38.8	38.8
Free Space Path Loss (dB)	136.6	128.1	112.5
Receive Antenna Gain (dBi)	6	6	6
Receive Line Losses (dB)	-2	-2	-2
Received Power (dBm)	-93.8	-85.3	-69.8
Receiver Noise Figure (dB)	8	8	8
External Noise Figure (dB)	1.3	1.3	1.3
System Noise Figure (dB)	10.1	10.1	10.1
Noise Floor - kT_0B (dBm)	-126.2	-126.2	-126.2
Receiver Noise Power (dBm)	-116.0	-116.0	-116.0
Theoretical E_b/N_0 (dB)	3.0	3.0	3.0
Theoretical C/N (dB)	3.6	3.6	3.6
Implementation Losses (dB)	2	2	2
Required C/N (dB)	5.6	5.6	5.6
Received C/N (dB)	22.2	30.7	46.3
Margin (dB)	16.6	25.1	40.7

Example: SRRC ($\alpha=0.5$) OQPSK with concatenated RS (255, 233) and rate $\frac{1}{2}$, $k=7$ convolutional FEC coding

- COCR and Eurocontrol FCS test service volumes similar in size to the notional architecture sector volumes were used to provide suitable total PIAC densities to determine total channel counts

Service Volume	Total PIAC	Volume (nmi ²)	Total Aircraft/nmi ²	UA Density: Aircraft/nmi ²	
				5%	10%
COCR - NAS Airport HD Phase 1	200				
COCR - NAS Airport LD Phase 1	12				
COCR - NAS Airport HD Phase 2	290				
COCR - NAS Airport LD Phase 2	19				
COCR - NAS TMA LD Phase 1	14	3,039	0.0046	0.0002	0.0005
COCR - NAS TMA HD Phase 1	16	2,831	0.0057	0.0003	0.0006
COCR - NAS En Route LD Phase 1	24	20,782	0.0012	0.0001	0.0001
COCR - NAS En Route HD Phase 1	24	5,119	0.0047	0.0002	0.0005
COCR - NAS TMA LD Phase 2	39	9,240	0.0042	0.0002	0.0004
COCR - NAS TMA HD Phase 2	44	7,691	0.0057	0.0003	0.0006
COCR - NAS En Route LD Phase 2	59	33,388	0.0018	0.0001	0.0002
COCR - NAS En Route HD Phase 2	45	10,132	0.0044	0.0002	0.0004
COCR - NAS En Route Super Sector	95	31,996	0.0030	0.0001	0.0003
Eurocontrol - TV1 Airport Total	290				
Eurocontrol - TV1a Airport Surface	264				
Eurocontrol - TV1 Airport in Flight	26	259	0.1004	0.0050	0.0100
Eurocontrol - TV2.1 - TMA Small	44	7,691	0.0057	0.0003	0.0006
Eurocontrol - TV2.2 - TMA Large	53	18,056	0.0029	0.0001	0.0003
Eurocontrol - TV3.1 - ENR Small	28	10,132	0.0028	0.0001	0.0003
Eurocontrol - TV3.2 - ENR Medium	62	33,739	0.0018	0.0001	0.0002
Eurocontrol - TV3.3 - ENR Large	204	134,957	0.0015	0.0001	0.0002
Eurocontrol - TV3.4 - ENR Super Large	522	539,829	0.0010	0.00005	0.0001



Calculated Total UAS C&C Communications Bandwidth



- Total calculated C&C communications bandwidth requirements were derived based on link budget results and computed UA aircraft densities

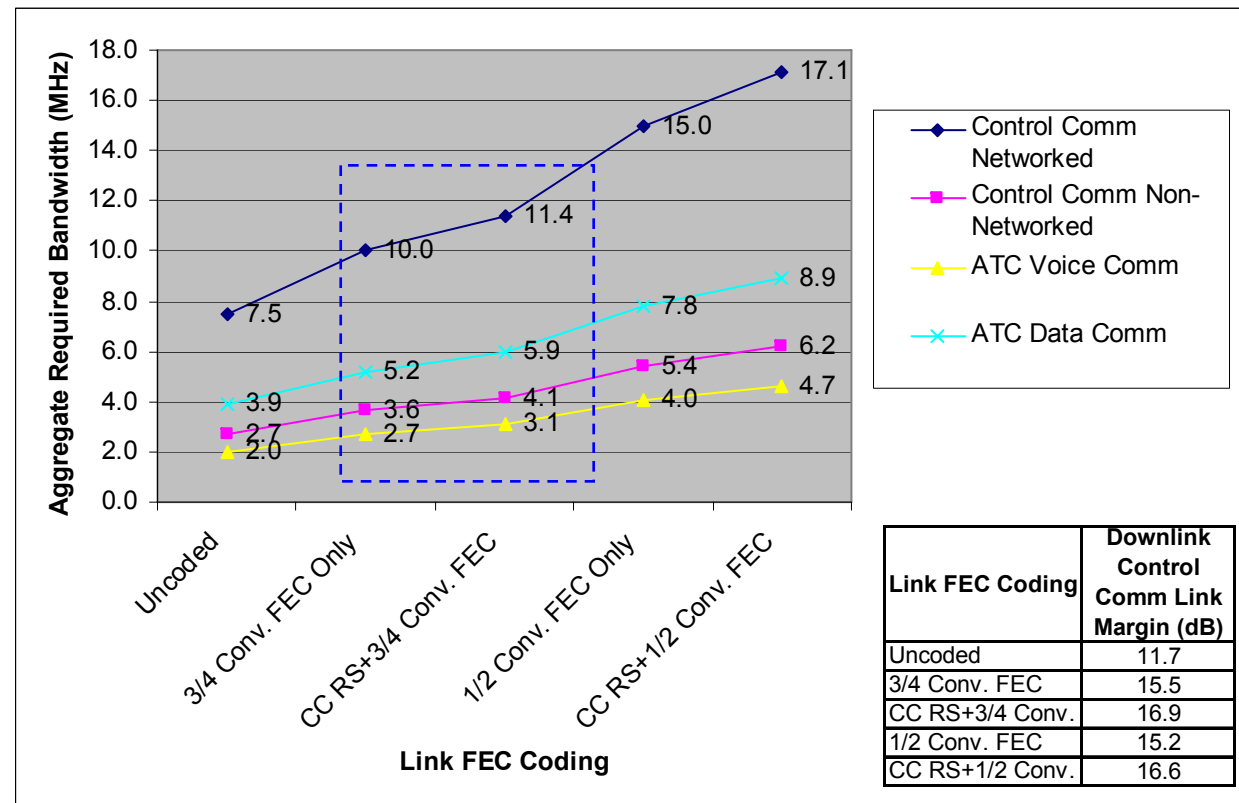
Sector Architecture Parameters	High Sector	Low Sector	Airport Surface	Total
Sector radius (nmi)	80	30		
Sector top (ft)	60000	5000		
Sector bottom (ft)	5000	0		
Sector height (nmi)	9.1	0.8		
Circular Sector area (nmi ²)	20,106	2,827		
Hexagonal Sector Area (nmi ²)	16,628	2,338		
Hexagonal Sector Volume (nmi ³)	150,511	1,924		
Cylindrical Sector Volume (nmi ³)	181,998	2,327		
Ratio: Circular/Hexagonal Area	1.21			
Radio line of sight at top (nmi)	301	87		
Radio line of sight at bottom (nmi)	87	0		
RLOS _{top} /RLOS _{bottom}	3.46			
RLOS _{top} /Sector radius	3.77	2.90		
Reuse Factor	9	7	1	
Reuse distance - 1 (Q - 1)	4.20	3.58		
Total Aircraft density (# per nmi ³)	0.00151	0.00565		
Percentage of UA in the NAS	10	10	10	
UAS Aircraft density (#UA per nmi ³)	0.000151	0.000565		
Computed Peak UA Count per Sector	23	1	26	
Control Link - Number of Downlink/Uplink Channels	207	7	26	240
Control Link - Downlink Channel Bandwidth (Hz)	60,800	60,800	60,800	60,800
Control Link - Uplink Channel Bandwidth (Hz)	10,600	10,600	10,600	10,600
Control Link - Total Downlink Bandwidth (Hz)	12,585,600	425,600	1,580,800	14,592,000
Control Link - Total Uplink Bandwidth (Hz)	2,194,200	74,200	275,600	2,544,000
Control Link - Total Uplink + Downlink BW (Hz)	14,779,800	499,800	1,856,400	17,136,000

Example: Total Required Control Communications Bandwidth Based on the Link Coding Parameters Used in the Example Link Budget

- Total required Control Communications bandwidth requirements were most sensitive to certain parameters:
 - UA peak counts
 - UA assumed to be 10% of the total PIAC; a different value linearly scales the results
 - Data rate requirements of the UAS Command & Status/Telemetry messages
 - These were highly dependent on update rates
 - Conservative values were assumed to upper bound the aggregate rate, based on low to moderate autonomy UAS
 - Locating the VSM on the UA (Configuration B) resulted in significant network and transport layer protocol overhead on the A/G links
 - Configuration A assumption that the VSM is located on the ground and that the UAS employs native/proprietary (i.e. non networked) link protocols significantly reduces required bandwidth
 - Link FEC coding, necessary to increase link margin to accommodate excess path losses impacted required channel bandwidth
 - A range of link FEC coding alternatives were used to provide a range of total required bandwidth

- The table below illustrates required total UAS C&C communications bandwidth estimates and their sensitivity to overhead and link FEC coding assumptions

Note: Box highlights best reasonable estimates



- It was not possible to derive a single number to estimate total UAS C&C bandwidth requirements
 - A range was provided to provide bounds, based on stated configurations and assumptions
 - For this architecture, the findings based on modest FEC coding, such as provided by the two rate $\frac{3}{4}$ cases seem to provide the most reasonable compromise between performance and bandwidth
 - In particular, the concatenated RS + $\frac{3}{4}$ rate convolution FEC coding provides significant excess path margin, plus additional protection against burst errors
- The notional architecture used to estimate total bandwidth requirements allowed for significant link margin because of the modest sector radii
 - Other architectures are possible and may be more efficient (the initial architecture resulted in poorer performance in almost every respect)
 - A detailed design was beyond the scope of this task
 - Co-site interference issues, not considered for this study, need to be explored
 - The potential impacts of sub-banding need to be addressed